SANDIA REPORT

SAND2015-6335
Unlimited Release
Printed July 30, 2015

Conceptual Waste Packaging Options for Deep Borehole Disposal

Jiann-Cherng Su
Ernest L. Hardin

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone:	(865) 576-8401
Facsimile:	(865) 576-5728
E-Mail:	reports@adonis.osti.gov
Online ordering:	http://www.osti.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd.
Springfield, VA 22161

Telephone:	(800) 553-6847
Facsimile:	(703) 605-6900
E-Mail:	orders@ntis.fedworld.gov
Online order:	http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online

SAND2015-6335
Unlimited Release
Printed July 30, 2015

CONCEPTUAL WASTE PACKAGING OPTIONS FOR DEEP BOREHOLE DISPOSAL

Jiann-Cherng Su
Ernest L. Hardin
Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-0747, USA

ABSTRACT

This report presents four concepts for packaging of radioactive waste for disposal in deep boreholes. Two of these are reference-size packages (11 inch outer diameter) and two are smaller (5 inch) for disposal of Cs/Sr capsules. All four have an assumed length of approximately 18.5 feet, which allows the internal length of the waste volume to be 16.4 feet. However, package length and volume can be scaled by changing the length of the middle, tubular section.

The materials proposed for use are low-alloy steels, commonly used in the oil-and-gas industry. Threaded connections between packages, and internal threads used to seal the waste cavity, are common oilfield types. Two types of fill ports are proposed: flask-type and internal-flush. All four package design concepts would withstand hydrostatic pressure of 9,600 psi, with factor safety 2.0. The combined loading condition includes axial tension and compression from the weight of a string or stack of packages in the disposal borehole, either during lower and emplacement of a string, or after stacking of multiple packages emplaced singly. Combined loading also includes bending that may occur during emplacement, particularly for a string of packages threaded together.

Flask-type packages would be fabricated and heat-treated, if necessary, before loading waste. The fill port would be narrower than the waste cavity inner diameter, so the flask type is suitable for directly loading bulk granular waste, or loading slim waste canisters (e.g., containing Cs/Sr capsules) that fit through the port. The fill port would be sealed with a tapered, threaded plug, with a welded cover plate (welded after loading). Threaded connections between packages and between packages and a drill string, would be standard drill pipe threads.

The internal flush packaging concepts would use semi-flush oilfield tubing, which is internally flush but has a slight external upset at the joints. This type of tubing can be obtained with premium, low-profile threaded connections at each end. The internal-flush design would be suitable for loading waste that arrives from the originating site in weld-sealed, cylindrical canisters. Internal, tapered plugs with sealing filet welds would seal the tubing at each end. The taper would be precisely machined onto both the tubing and the plug, producing a metal-metal sealing surface that is compressed as the package is subjected to hydrostatic pressure. The lower plug would be welded in place before loading, while the upper plug would be placed and welded after loading.

Threaded connections between packages would allow emplacement singly or in strings screwed together at the disposal site. For emplacement on a drill string the drill pipe would be connected directly into the top package of a string (using an adapter sub to mate with premium semi-flush tubing threads). Alternatively, for wireline emplacement the same package designs could be emplaced singly using a sub with wireline latch, on the upper end. Threaded connections on the bottom of the lowermost package would allow attachment of a crush box, instrumentation, etc.

TABLE OF CONTENTS

ABSTRACT iii
TABLE OF CONTENTS v
FIGURES vi
TABLES vi
ACRONYMS AND ABBREVIATIONS vii
1. INTRODUCTION 9
2. WASTE PACKAGING DESIGN CONSTRAINTS 11
3. EFFECT OF AXIAL STRESSES ON COLLAPSE PRESSURE OF THE PACKAGE 15
4. PACKAGING CONCEPTS 19
4.1 Option 1 – 10.75-Inch OD Flask-Type Waste Package for Bulk Waste 19
4.1.1 Stress Analysis for Option 1 21
4.1.2 Option 1 Pros 21
4.1.3 Option 1 Cons 21
4.2 Option 2 – 10.75-Inch OD Internal-Flush Type Waste Package for Canistered Waste 22
4.2.1 Option 2 Pros 23
4.2.2 Option 2 Cons 23
4.3 Option 3 – 5-Inch OD Flask-Type Waste Package for 2.6-Inch OD Cs/Sr Capsules 25
4.3.1 Stress Analysis for Option 3 25
4.3.2 Option 3 Pros 26
4.3.3 Option 3 Cons 26
4.4 Option 4 – 5-Inch OD Internal-Flush Type Waste Package for 3.3-Inch OD Cs/Sr Capsules 26
4.4.1 Option 4 Pros 28
4.4.2 Option 4 Cons 28
5. MODULAR ENHANCEMENTS FOR PACKAGES 29
5.1 Fishing Adapter and Crush Box for Wireline Emplacement 29
6. REFERENCES 31
DISTRIBUTION 32

FIGURES

Figure 1. Borehole curvature illustration (Gourgoyne, Jr., Adam T., Applied Drilling Engineering, Chapter 7: Casing Design). 16

Figure 2. Reduction in collapse pressure due to build rate. 17

Figure 3. Option 1 (shown as 2 packages with aspect ratio shortened for illustration). 20

Figure 4. Option 1 details (Aspect ratio shortened for illustration). 20

Figure 5. Option 1 shown at true aspect ratio. 20

Figure 6. Stress analysis of Option 1 (9600 psi external pressure, 153,000 lbf tension. Aspect ratio shortened for illustration). 21

Figure 7. Option 2, (shown as 2 packages with aspect ratio shortened for illustration). 22

Figure 8. Option 2 details (Aspect ratio shortened for illustration) Stress Analysis for Option 2.23

Figure 9. Design Option 2 simulation loads and mesh (Aspect ratio shortened for illustration). .24

Figure 10. Option 2 simulation results (Aspect ratio shortened for illustration). 24

Figure 11. Option 3 (shown as 2 packages with aspect ratio shortened for illustration). 25

Figure 12. Option 3: Small diameter overpack with eight Cs/Sr capsules packed axially. 25

Figure 13. Option 3 stress analysis (Aspect ratio shortened for illustration). 26

Figure 14. Option 4 (shown as 2 packages with aspect ratio shortened for illustration). 27

Figure 15. Design Option 4 stress analysis (aspect ratio shortened for illustration). 28

Figure 16. Modular Crush Box and Wireline Latch/Fishing Overshot. 29

Figure 17. Package assembly for lowered individually on wireline (aspect ratio shortened for illustration). 30

TABLES

Table 1. Collapse pressure for tubular portion of packages (110 ksi yield strength material) 16

ACRONYMS AND ABBREVIATIONS

API	American Petroleum Institute
Cs/Sr	Cesium and strontium (mainly Cs-137 and Sr-90)
DBFT	Deep Borehole Field Test
DBD	Deep Borehole Disposal
DOE	U.S. Department of Energy
ft	feet
ID	inner diameter
km	kilometer
ksi	kilo pounds per square inch
lbf	pounds force
m	meter
OD	outer diameter
psi	pounds per square inch

CONCEPTUAL WASTE PACKAGING OPTIONS FOR DEEP BOREHOLE DISPOSAL July 30, 2015

1. INTRODUCTION

This report presents conceptual designs for waste packages for the Deep Borehole Field Test (DBFT) based on consideration of deep borehole disposal (DBD) of certain DOE-owned waste forms. One or more of the concepts presented here could be selected for final design, fabrication, testing, and test emplacement and retrieval in a deep borehole as part of the DBFT.

The DBFT is an ongoing research and development project, to evaluate the technical feasibility of waste disposal in crystalline basement rock, using boreholes drilled to a depth below surface of approximately 16,400 ft (5 km). In this disposal concept, waste packages would be emplaced in the lower 6,560 ft (2 km) of the borehole. Intervals above the waste would be plugged and sealed (Arnold et al. 2011). The DBFT will not involve the use of any radioactive wastes, however, waste packages will be developed and tested for efficacy and durability during emplacement and retrieval operations.

Waste Packaging Nomenclature

In this study the term *disposal overpack* refers to a heavy-wall, sealed container that withstands the downhole environment, and contains one or more thin-wall waste canisters. Waste canisters will be loaded and sealed at the point of origin for the waste, and may contain Cs/Sr capsules, or bulk granular waster forms. Such pre-packaged wastes are identified as *canistered wastes*. The disposal overpack could be loaded and sealed at an upstream hot-cell facility (not necessarily at the waste point-of-origin since the canistered waste could be readily transported).

Alternatively, bulk granular waste such as the DOE-owned, granular calcine waste form, could be loaded directly into a heavy-wall *waste package* at the point of origin using a design concept such as the flask-type described below. The waste package would be sealed in a hot-cell facility at the waste point-of-origin.

The term *waste package* is also used more generally for the final, sealed vessel, that is ready for emplacement in a deep borehole, regardless of its size or whether it is a flask-type or internal-flush design.

All four packaging concepts presented in this report are intended to ensure that the waste is isolated from the borehole, in a one-atmosphere pressure environment, at downhole temperature, in a 16,400 ft deep borehole containing fluid that has density 1.3 times that of pure water, for at least 10 years. Additional design requirements for these waste packages are presented in Section 2.

2. WASTE PACKAGING DESIGN CONSTRAINTS

The current requirements for waste packaging are presented in the *Deep Borehole Field Test Requirements and Controlled Assumptions* (Hardin 2015) with supplemental information in *Handling and Emplacement Options for Deep Borehole Disposal Conceptual Design* (Cochran and Hardin 2015). Key constraints from these reports are summarized below. English units are used intentionally in this report because of their prevalence in the drilling industry.

Two borehole sizes are considered in this study, based on previous conceptual designs (Arnold et al. 2011, 2014). The larger, reference size would have 17-inch diameter in the disposal zone, with a 13.375-inch guidance casing extending from the surface to total depth. Waste packages would maintain 0.7-inch radial clearance with the drift ID (clearance ID) of the guidance casing, giving a maximum OD for the packages of approximately 11 inches. This OD could be exceeded locally for collars or other features of small size, as shown in some of the figures below.

The smaller size borehole considered in this study would have 8.5-inch diameter in the disposal zone, with a 7-inch diameter guidance casing. Waste packages would maintain 0.7-inch radial clearance with the casing drift ID, giving a maximum OD of approximately 5 inches.

The upper end of every waste package will include a 1-ft thick shield plug (if made of steel) and the lower end will include an end plug with axial length as needed for structural strength.

Waste package length has not been finalized. The overall external length used in this report is 18.5 ft, which includes an internal waste cavity length of 16.4 ft (5 m), the shield plug and lower end plug, connection threads, and a small separation of welds from connector threads to limit heat damage. The 18.5-ft overall length is nominal, and the package length can be readily adjusted by varying the length of the tubular portion of the package. Package length for the DBFT will be selected to demonstrate performance of packaging and emplacement systems that can accommodate commercial spent nuclear fuel (see Arnold et al. 2011). Also, package length may be limited so as to limit the length and weight of a shipping cask for strong gamma-emitting high-level waste.

The exterior surfaces of waste packages, including connections, will be smooth and free of steps or ridges that could hang up on casing joints, hangers, etc., when moving upward or downward. All packages will have a groove or collar at the lower end, which engages with the “elevator” ram to support the package string during assembly (Cochran and Hardin 2015). The depth of such grooves (or the radial thickness of collars) will be approximately 0.5 inch. In addition, all packages will have a collar at the upper end (or upset, in the case of the internal-flush designs using semi-flush tubing) to engage the basement slips (Cochran and Hardin 2015).

At 16,400 ft depth the in situ temperature could be as high as 338° F (170°C, see Hardin 2015). For heat-generating waste the peak package surface temperature could be 480°F (250°C). This latter temperature is based on thermal analysis by Arnold et al. (2014) for packages containing Cs/Sr capsules stacked end-to-end.

For design purposes it is assumed that the borehole pressure will be less than or equal to that produced by a uniform fluid column with 1.3× the density of pure water, at 16,400 ft depth. The resulting design basis hydrostatic pressure at the bottom of the borehole is 9,600 psi. This fluid density is not the heaviest that could be used, since the fluid could be intentionally stratified during emplacement and plugging/sealing operations.

If 40 reference-size waste packages (11-inch OD) are assembled in a string and hung in the borehole, the axial tensile loading from the combined weight is estimated to be approximately 153,000 lb (buoyant weight in pure water; Cochran and Hardin 2015). A compressive load of similar magnitude will be produced when the package string is emplaced on the bottom, at rest.

When a string of packages is set down and disconnected from the drill pipe, the compressive load on packages from the weight of drill pipe is controlled by the rig hook load, as well as friction between the string and the guidance casing. This load will be controlled in order to limit compressive loading of the waste packages, however, design should consider the full load of the drill string. Engineered measures to prevent load surge through the package string could be implemented, such as a crush-box at the bottom of each string which would reduce hook load by a detectable amount and limit load on the bottom (unless the maximum range of crush-box deformation was reached).

The selection of up to 40 waste packages in a string is a remnant of previous studies (Arnold et al. 2011). Such a limit controls the total weight of the drill string during emplacement, and also controls the column loads on the guidance casing between cement plugs. A greater number makes more efficient use of the disposal zone interval by limiting the number of cement plugs. The number could be adjusted up or down based on engineering analysis and safety considerations.

If forty smaller (5-inch OD) waste packages are assembled in a string in the top of the borehole, the axial loading from the combined weight of the waste packages will be approximately 28,000 lb (buoyant weight in pure water). For this calculation it is assumed that each waste package contains eight Cs/Sr capsules, and that each capsule weighs up to 20 kg with canister or basket hardware (the weight of each capsule is 10 kg or less; E. Hardin, personal communication).

A minimum factor of safety of 2.0 will be used for mechanical analyses of the waste packages (Hardin 2015). Packages and connections between packages (if applicable) will have sufficient strength to withstand mechanical loads during emplacement, retrieval, and fishing of stuck packages (or package strings, if packages are threaded together).

The use of standard threaded connections on both ends of the packaging will allow multiple emplacement options. The packages can be emplaced singly, or threaded together into a string of packages for emplacement (and retrieval). Drill pipe can connected directly into the top of a waste package for drill-string emplacement, or an adapter can be connected to the top of a waste package for wireline emplacement. For drill pipe connections, it is assumed that 4-1/2 inch drill pipe would be used.

Package connections for drill-string emplacement will include: 1) a threaded connection to the packages below; and 2) a threaded connection to drill pipe above for emplacement or fishing. Package connections for wireline emplacement of single packages will include a releasable cable head and a fishing neck on top, and a threaded connection on the bottom for attaching additional hardware such as instrumentation, centralizers, shock absorbing materials, etc. Whereas multiple packages could be emplaced with a wireline (and meet service load limits), it would require a means to thread packages together at the surface which would significantly to cost and complexity.

Waste packages will be loaded and sealed by welding at specialized nuclear material handling facilities. They will be delivered to the disposal site sealed, with proper adapters attached, in condition ready for direct emplacement in the disposal borehole. Welding provides a permanent seal and has been a preferred closure solution for mined geologic disposal in repository R&D programs. The addition of adapters to waste packages (e.g., a sub with wireline latch and fishing neck as discussed below) must be accommodated by the internal dimensions of the shipping cask.

To simplify design and fabrication, oilfield tubing or casing will be used for the tubular portion of the packages. For the packages with a maximum OD of 11 inches, the conventional tubing size is 10.75-inch OD x 8.75-inch ID. For the smaller packages the conventional casing size is 5-inch OD x 4.0-inch ID.

As stated above, the packages must be designed for axial loads (153,000 or 28,000 lb), transient load surges during emplacement, and hydrostatic pressure of 9,600 psi. If the package is subjected to bending (because the guidance casing is curved relative to the length of the package) then there are additional tensile and compressive loads that the package must withstand. The effects from these axial loads on the collapse strength of the tubular portion of the packages is addressed in Section 3.

3. EFFECT OF AXIAL STRESSES ON COLLAPSE PRESSURE OF THE PACKAGE

According to Section 2 of API Bulletin 5C3 (Bulletin on Formulas and Calculations for Casing, Tubing, Drill Pipe, and Line Pipe Properties - Sixth Edition), the yield strength collapse pressure for a pipe under external pressure is given by Equation (3-1). This pipe analysis is applicable to the tubular portion of the packaging and is valid for diameters divided by wall thicknesses (D/t) ratios < 12.42 and a material with a steel grade of P-110.

$$P_{yp} = 2Y_p \left[\frac{\left(D/t \right) - 1}{\left(D/t \right)^2} \right] \tag{3-1}$$

If the pipe is also subjected to tensile axial stress, then the collapse pressure is reduced and becomes:

$$P_{CA} = P_{yp} \left[\sqrt{1 - 0.75 \left[\frac{\left(S_A + P_i \right)}{Y_p} \right]^2} \right] - 0.5 \left(\frac{S_A + P_i}{Y_p} \right) \tag{3-2}$$

If the effect of borehole curvature is considered, then there is additional tensile stress on the pipe due to bending. The build rate or dogleg severity is typically given in °/100 ft. For a given build rate, the radius of curvature of the borehole is given by Equation (3-4).

$$\alpha = \frac{x^{\circ}}{100 ft} \tag{3-3}$$

$$\rho = \frac{180}{\pi \cdot \alpha} \tag{3-4}$$

According to beam theory, the bending moment imparted on the package is:

$$M = \frac{E \cdot I}{\rho} \tag{3-5}$$

where E is the modulus of elasticity, I is the area moment of inertia, and ρ is the radius of curvature. From that, the normal stress at the outer diameter of the pipe is given by Equation (3-6):

$$\left(\sigma_z \right)_0 = \frac{M \cdot \left(OD/2 \right)}{I} \tag{3-6}$$

For a drill string in contact with casing, the pipe is subject to non-uniform bending. If it is assumed that the contact between the package and the casing occurs at the joints (Figure 1), then the additional tensile stress caused by point-loaded bending is given by Equation (3-8) (Gourgoyne, Jr., Adam T., *Applied Drilling Engineering*):

$$K = \sqrt{\frac{F_a}{EI}} \tag{3-7}$$

$$(\sigma_z)_{\max} = (\sigma_z)_0 \frac{6KL_j}{\tanh\left(6KL_j\right)} \tag{3-8}$$

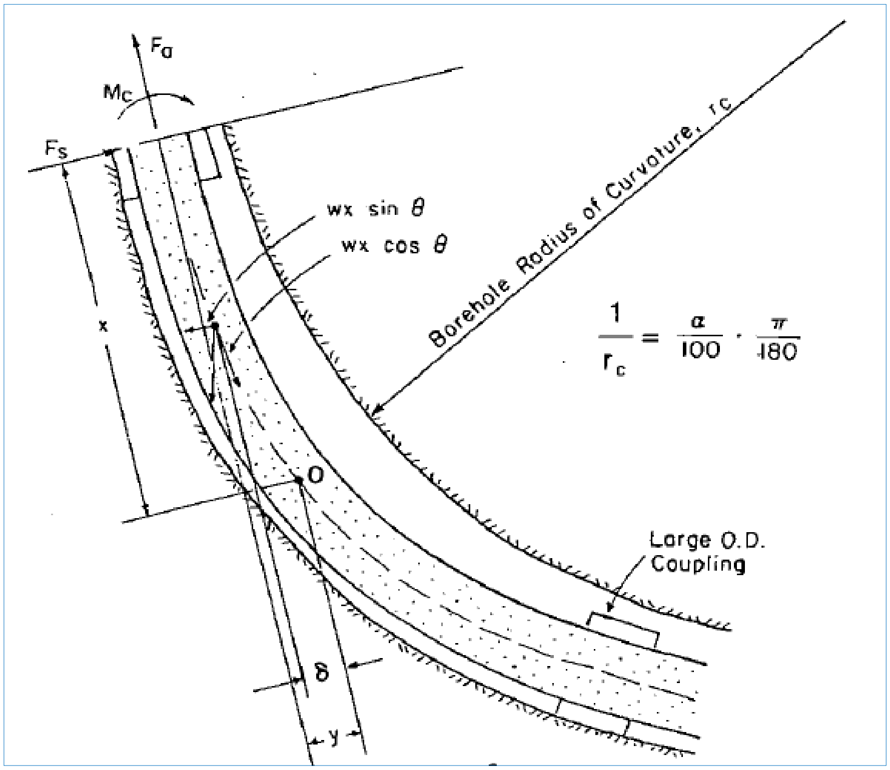


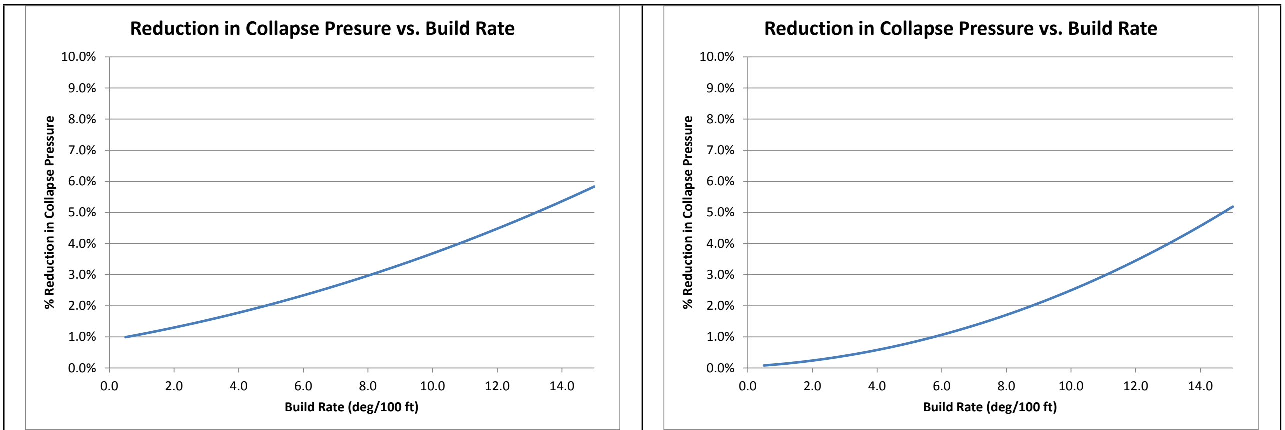
Figure 1. Borehole curvature illustration (Gourgoyne, Jr., Adam T., Applied Drilling Engineering, Chapter 7: Casing Design).

Based on the operational requirements, nominal 11-inch OD packages and 5-inch OD packages are considered for analysis. The appropriate tubing or casing dimensions are used as the basis for the collapse pressure estimates shown in Table 1. Each design concept provides a factor of safety of approximately 2.0 against yielding due to external hydrostatic load of 9,560 psi, with 110 ksi steel.

Table 1. Collapse pressure for tubular portion of packages (110 ksi yield strength material)

OD (inches)	ID (inches)	Nominal Collapse Pressure (psi)
10.75	8.75	18,560
5.0	4.0	19,600

The anticipated effect of temperature is a reduction in yield strength of the material and a corresponding decrease in the factor of safety. The exact reduction will depend on the final material selected for the package.



5.0” OD Casing (19,600 psi collapse)	10.75” OD Tubing (18,560 psi collapse)

Figure 2. Reduction in collapse pressure due to build rate.

Figure 2 shows that bending of the package, due to a curvature of the guidance casing (as illustrated in Figure 1), will have minimal effect on the collapse strength of the tubular portion of the packaging.

4. PACKAGING CONCEPTS

Using the package outer diameters of 10.75 and 5 inches from the previous section as a starting point, four package concepts are presented based on the emplacement method options and packaging constraints described in Section 2. The packaging options are

- Option 1 (Section 4.1) – 10.75-inch OD flask-type waste package for bulk waste, for use with a 13.375-inch OD guidance casing
- Option 2 (Section 4.2) – 10.75-inch OD internal-flush type package for canistered waste, for use with a 13.375-inch OD guidance casing
- Option 3 (Section 4.3) – 5-inch OD flask-type package for stacked 2.6-inch OD Cs/Sr capsules, for use with a 7-inch OD guidance casing
- Option 4 (Section 4.4) – 5-inch OD internal-flush type package for stacked, Cs/Sr capsules up to 3.3-inch OD, for use with a 7-inch OD guidance casing

4.1 Option 1 – 10.75-Inch OD Flask-Type Waste Package for Bulk Waste

Option 1 is a reference-size, 10.75-inch OD flask-type waste package for bulk waste, for use with a 13.375-inch OD guidance casing. Option 1 uses conventional API tool joints (API regular or numbered) and attaches them to the tubular package body via friction welding (Figure 3). This manufacturing technique is commonly used to construct drill pipe ends. A chamfer is included on the inboard end of each end plug so that the massive plug does not interfere with friction welding by acting as a heat sink.

The package would have a box thread on top and a pin thread on the bottom. For the 10.75-inch OD package design, an API NC77 or equivalent thread could be used. This arrangement provides a smooth exterior package profile. For drill-string emplacement a detent collar groove would be machined in the lower end plug, and a collar machined on the upper end plug, to provide redundant points for gripping the package in the basement slips and pipe ram during package string assembly.

Granular waste could be loaded through the fill port on the upper (box) end of the package (Figure 4). A tapered, threaded plug would then be threaded into the port for initial containment of the waste. A cover plate would be welded over the plug. The true aspect ratio of Option 1 (length to diameter) is shown in Figure 5.

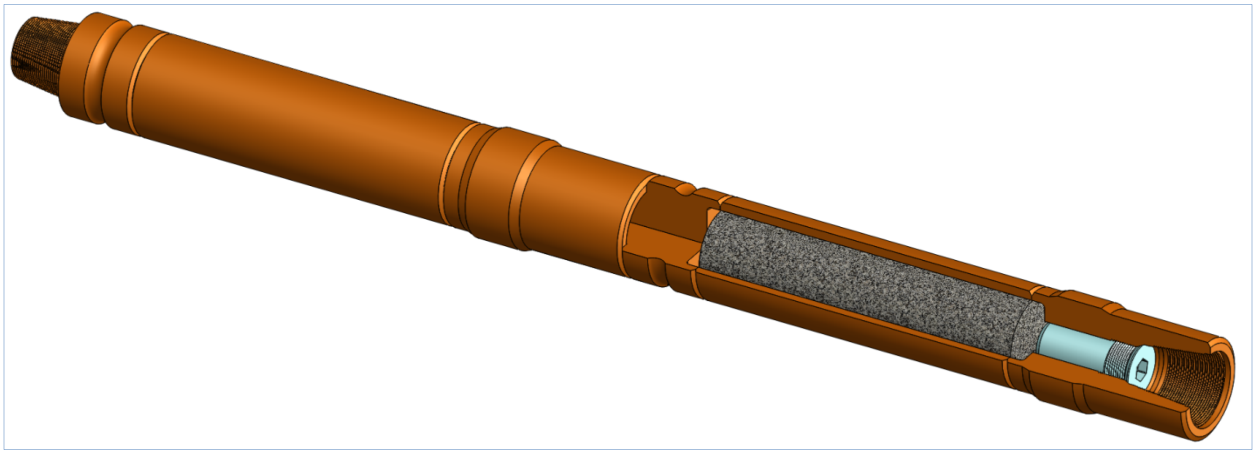


Figure 3. Option 1 (shown as 2 packages with aspect ratio shortened for illustration).

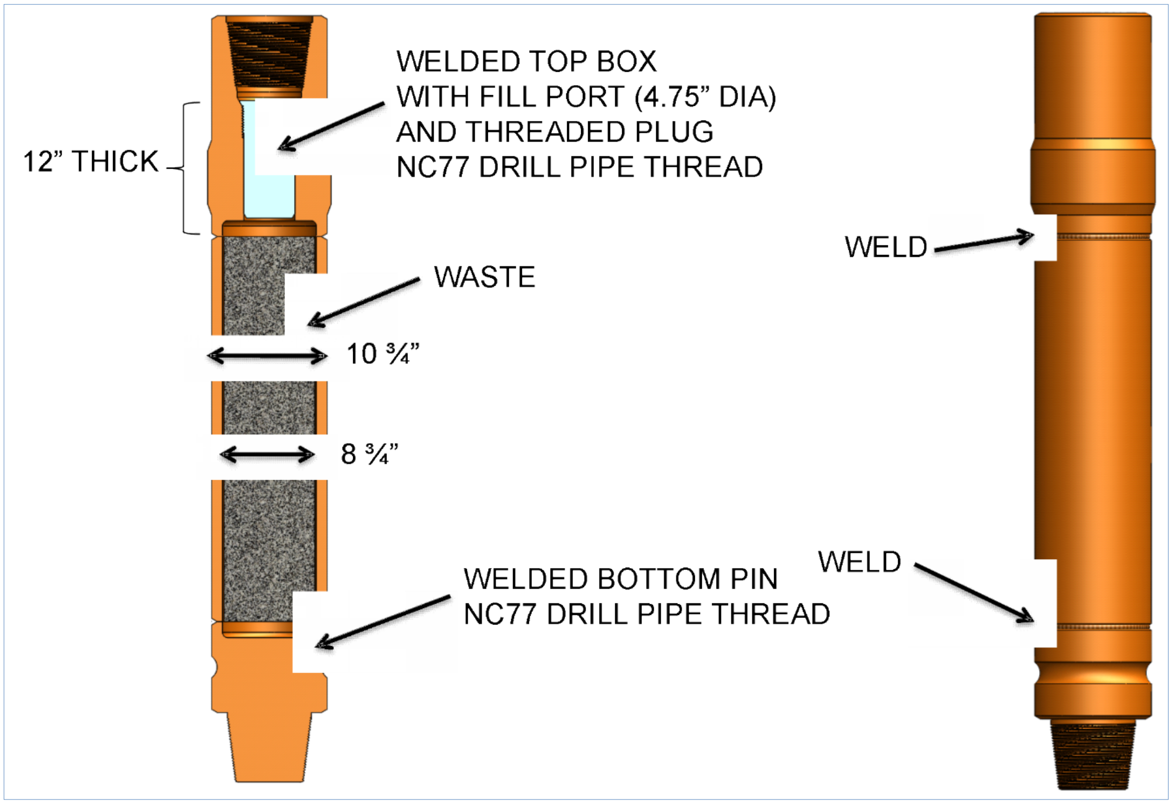


Figure 4. Option 1 details (Aspect ratio shortened for illustration).

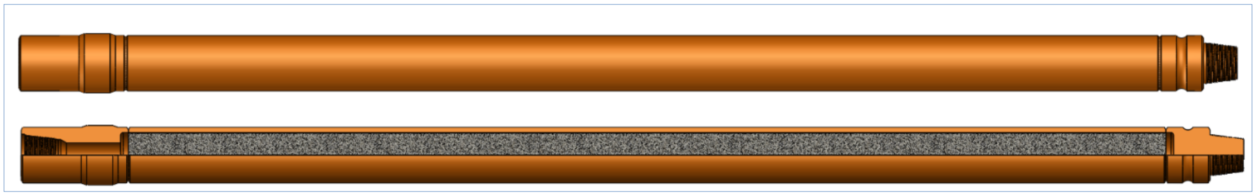


Figure 5. Option 1 shown at true aspect ratio.

4.1.1 Stress Analysis for Option 1

A stress analysis of the design was performed using Solidworks Simulation. An external pressure of 9,600 psi was applied over the exterior surfaces. An axial force of 153,000 lbf was applied through the threaded connection. The results of the stress analysis are shown in Figure 6. As expected, the highest von Mises stresses are in the tubular section of the package. The external loads result in a von Mises stress of around 58 ksi at the inner wall of the package. With a material yield strength of 110 ksi, this provides a FoS around 1.9. This is consistent with the analytical solutions presented in the previous section.

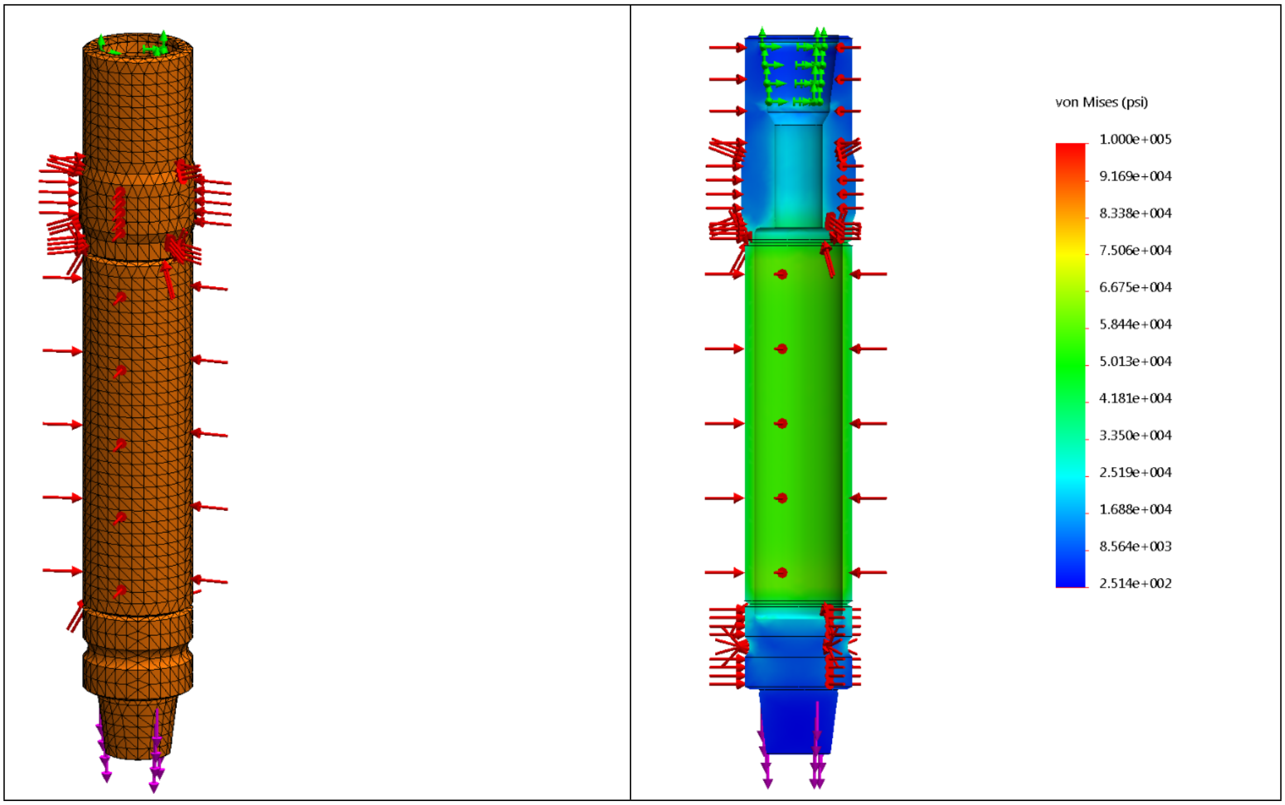


Figure 6. Stress analysis of Option 1 (9600 psi external pressure, 153,000 lbf tension. Aspect ratio shortened for illustration).

4.1.2 Option 1 Pros

- Relative ease of manufacturing and assembly
- Heat treatment of structural welds possible before waste loading
- Standard API tool joints are designed for repeated makeup/breakout
- Smooth exterior, but gripping features can be machined into the end plugs
- Use of detent at lower end plug (instead of collar) reduces impact on radial clearance

4.1.3 Option 1 Cons

- Welds in axial load path
- Sealing between joints requires pipe dope

4.2 Option 2 – 10.75-Inch OD Internal-Flush Type Waste Package for Canistered Waste

Option 2 is a 10.75-inch OD internal-flush type overpack for canistered waste, for use with a 13.375-inch OD guidance casing. Option 2 uses an external upset semi-flush casing with welded internal plugs to contain canistered waste (Figure 7). The threaded connection would be a Tenaris MAC II® or equivalent. The dovetail shaped threads provide a tight seal against external pressure, but are not ideal for repeated makeup/breakout applications. To prevent damage to the threads when the plugs are installed, the closure welds would be recessed beyond the threaded portion of of the body tube (Figure 8).

The waste would be contained by a plug welded in place after waste loading. Note that for a 10.75-inch OD casing the external upset diameter is 11.23 inches, providing approximately 0.1 inches less radial clearance with the guidance casing than the current design requirement (Hardin 2015, Section 1.10).

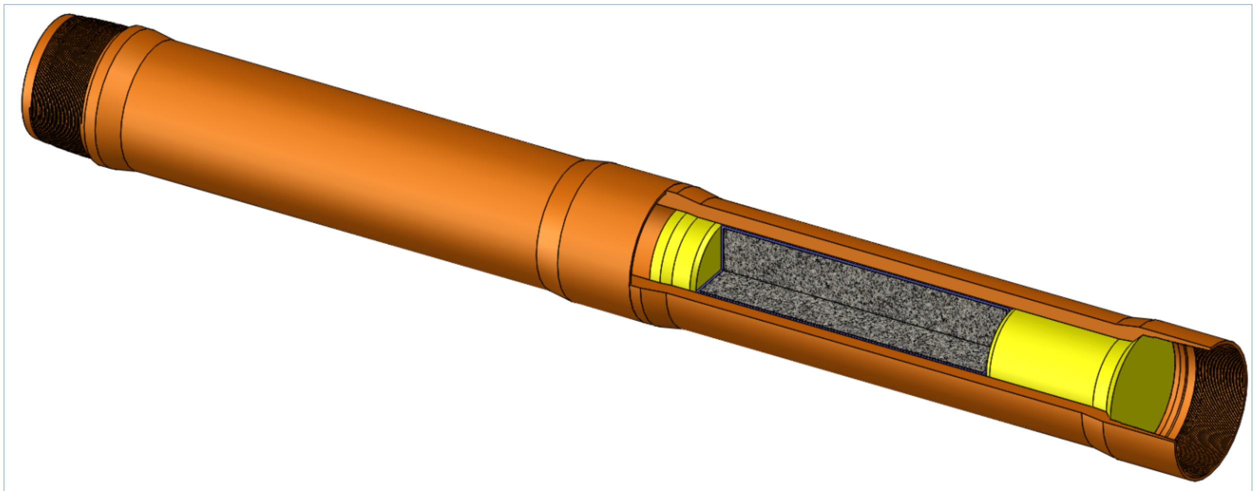


Figure 7. Option 2, (shown as 2 packages with aspect ratio shortened for illustration).

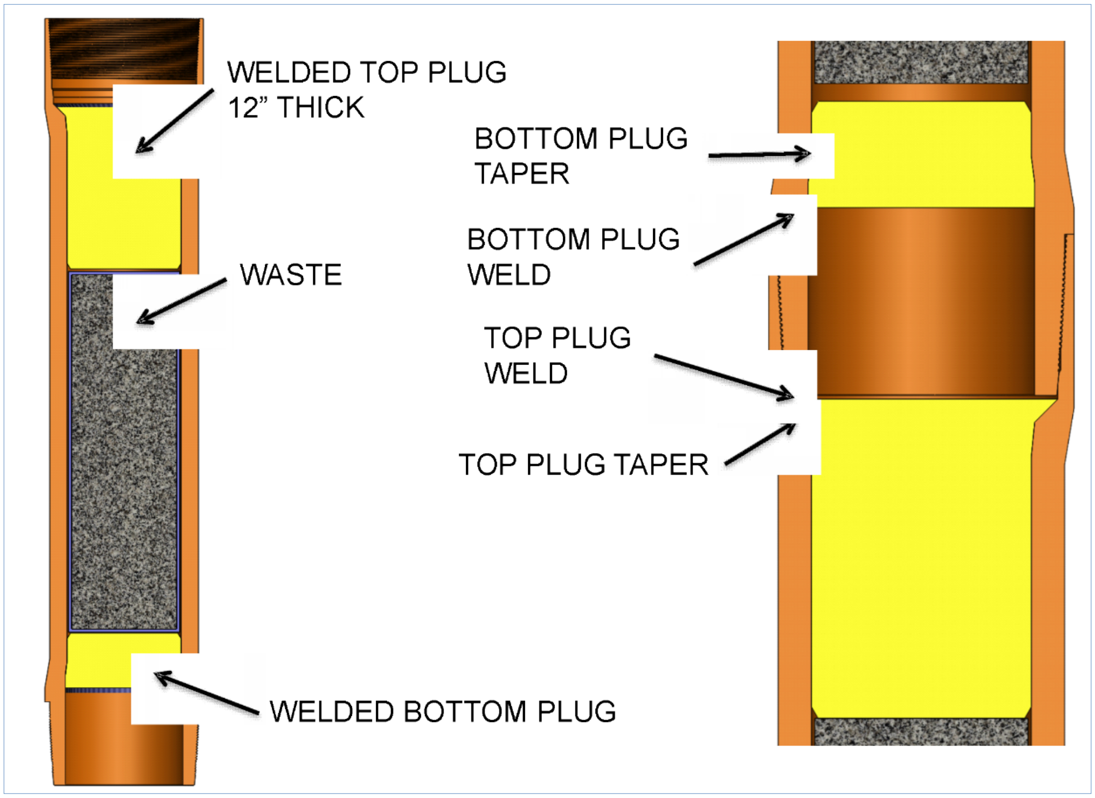


Figure 8. Option 2 details (Aspect ratio shortened for illustration) Stress Analysis for Option 2.

Two configurations were analyzed: 1) threaded connections between packages leak, so that borehole pressure reaches the internal plugs (Figure 9); and 2) threaded connections between packages do not leak. The contact between the plugs and the overpack body is treated as a bonded line contact at the weld. The rest of the contact between the plug and body is treated as a non-penetrating interface between bodies. If external pressure reaches the plugs, the von Mises stress at the interior surface of the tubing is approximately 40 ksi (Figure 10). If the connection does not leak, the maximum stress is approximately 46 ksi. This reduction in overall stress occurs because the compressive axial load imparted by the external pressure acting directly on the plugs reduces the net stress on the overpack.

4.2.1 Option 2 Pros

- Based on standard size casing
- No welds in axial load path
- Dovetail threads provide good sealing against external pressure

4.2.2 Option 2 Cons

- Combination of size (10.75-inch OD), material (110 ksi yield), and connections would likely require a custom mill run
- Dovetail threads not designed repeated assembly/disassembly

- External upset increases OD beyond the 11-inch maximum diameter requirement

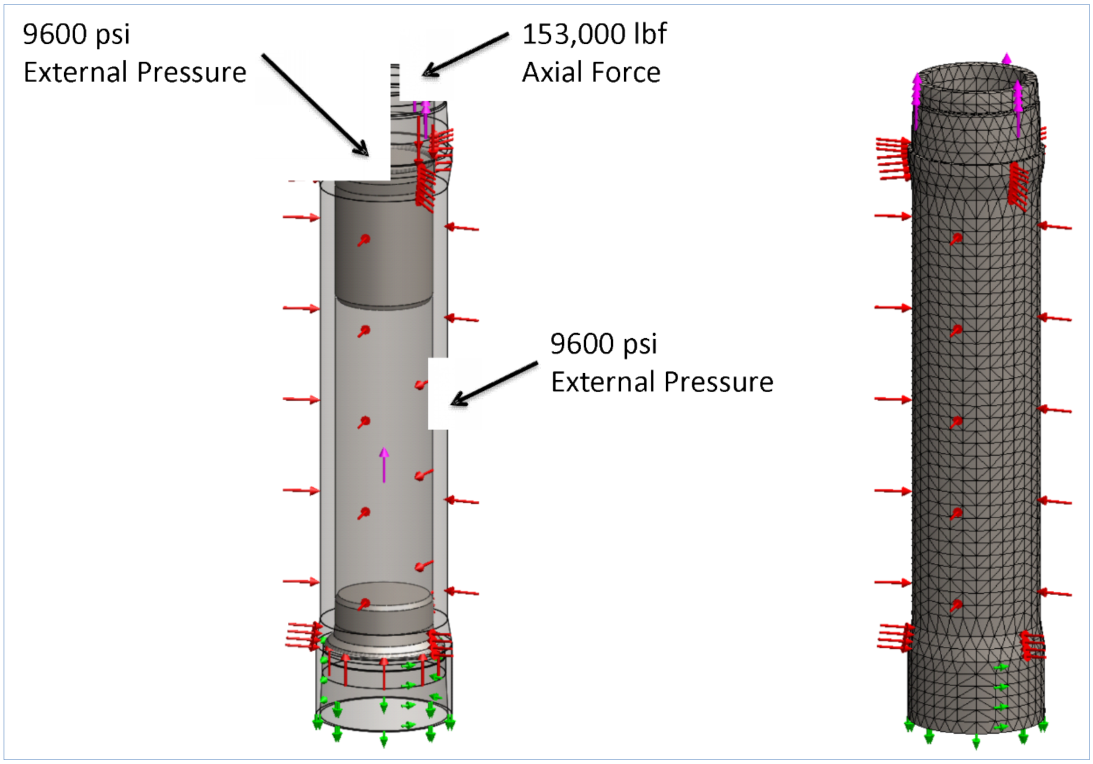


Figure 9. Design Option 2 simulation loads and mesh (Aspect ratio shortened for illustration).

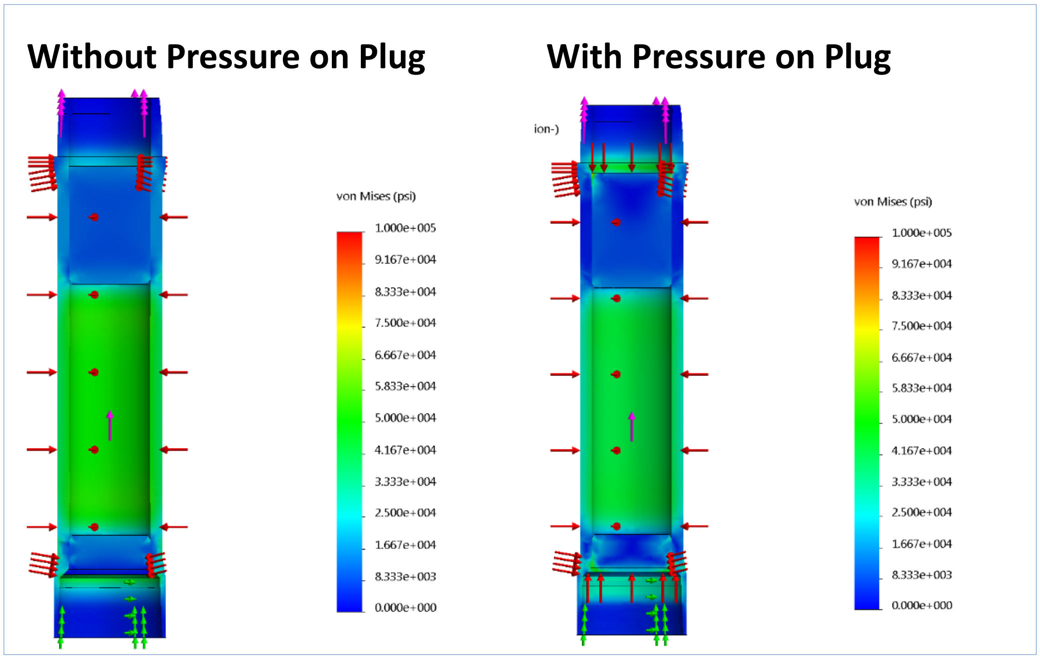


Figure 10. Option 2 simulation results (Aspect ratio shortened for illustration).

4.3 Option 3 – 5-Inch OD Flask-Type Waste Package for 2.6-Inch OD Cs/Sr Capsules

Option 3 is a flask-type overpack designed for 2.6-inch OD Cs/Sr capsules inside a 5-inch OD overpack. Option 3 is a smaller version of Option 1, sized to receive eight Cs/Sr capsules stacked end-to-end (Figure 11). The overpack would be based on 5-inch OD x 4-inch ID casing, with welded end plugs at each end. The threaded connections at each end would be API NC38 or equivalent, providing a smooth exterior surface. The friction welded fabrication method, and provisions for welding in the end plug design, would be the same as for Option 1. For drill-string emplacement a detent collar groove would be machined in the lower end plug, and a collar machined on the upper end plug, to provide redundant points for gripping the package in the basement slips and pipe ram during package string assembly.

The welded box end has a fill port to allow loading of Cs/Sr capsules (which may be enclosed in a thin-wall canister), possibly with an internal basket for stabilization. A tapered, threaded plug would then be threaded into the port for initial containment of the waste. A cover plate would be welded over the plug. The true aspect ratio of Option 3 (length to diameter) is shown in Figure 12.

4.3.1 Stress Analysis for Option 3

A 9,600 psi external pressure is applied over the entire overpack, and an axial compressive load of 28,000 lb. The stress analysis results are consistent with the analytical calculations for external pressure and axial loading (Figure 13). For the combined loading, the maximum von Mises stress at the inner wall of the casing is approximately 43 ksi. For material with 110 ksi yield strength, this results in a factor of safety of approximately 2.6.

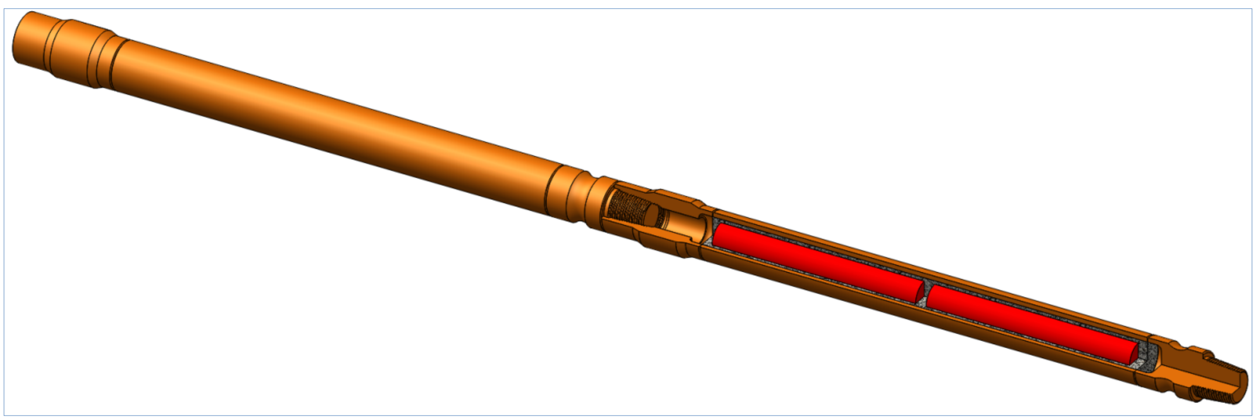


Figure 11. Option 3 (shown as 2 packages with aspect ratio shortened for illustration).

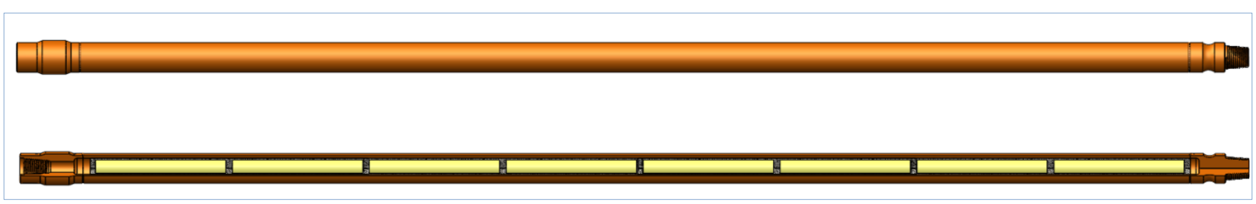


Figure 12. Option 3: Small diameter overpack with eight Cs/Sr capsules packed axially.

4.3.2 Option 3 Pros

- Relative ease of manufacturing and assembly
- Heat treatment of structural welds possible before waste loading
- Standard API tool joints are designed for repeated makeup/breakout
- Smooth exterior, but gripping features can be machined into the end plugs
- Use of detent at lower end plug (instead of collar) reduces impact on radial clearance

4.3.3 Option 3 Cons

- Welds in axial load path
- Sealing between joints requires pipe dope

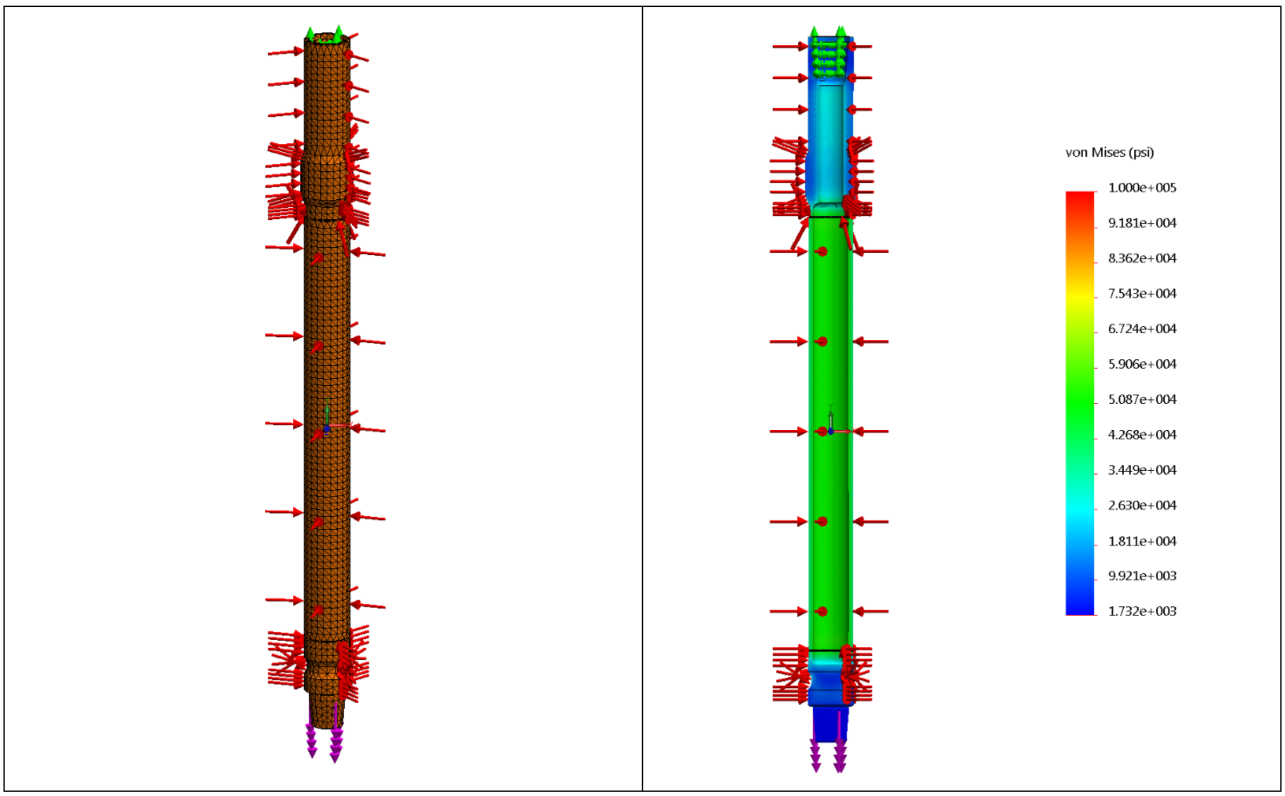


Figure 13. Option 3 stress analysis (Aspect ratio shortened for illustration).

4.4 Option 4 – 5-Inch OD Internal-Flush Type Waste Package for 3.3-Inch OD Cs/Sr Capsules

Option 4 is an overpack option for the larger (up to 3.3-inch OD) Cs/Sr capsules. This design is based on commercial casing with a 5.0-inch OD x 4.0-inch ID (Figure 14). The connection is a Tenaris Wedge 513® which uses dovetail shaped threads, and is both internally and externally fluxh. The rated collapse pressure for the casing is 19,800 psi. To prevent damage to the threads when the end plugs are installed, the closure welds would be recessed beyond the threaded portion of of the body tube (see Figure 8 for similar arrangement). The dovetail shaped threads provide a tight seal against external pressure, but are not ideal for repeated makeup/breakout applications.

Similar to Option 2, the canisters would use a welded end plug to contain the contents after loading. For the nominal 18.5-ft length, these overpacks could be loaded with up to eight Cs/Sr capsules (like Option 3).

With flush casing the wall thickness does not allow for cutting detent grooves for holding the package in the basement. Accordingly, for drill-string emplacement external collars would be welded at the upper and lower ends for gripping by the slips and pipe ram. For collar height of 0.25 inches, this would provide approximately 0.25 inches less radial clearance with the guidance casing than the current design requirement (Hardin 2015, Section 1.10).

Stress Analysis for Option 4

The loading conditions for the analysis are the same as in the previous section. A 9,600 psi external pressure is applied over the entire overpack. Axial load of 28,000 lb is applied at the joint. For stress analysis, the borehole pressure is assumed to reach the inner plugs which leads to greater maximum stress in the body tube.

The stress analysis results are consistent with the analytical calculations for external pressure and axial loading (Figure 15). For the combined loading, the maximum von Mises stress at the inner wall of the tubing is approximately 42 ksi. For a material with 110 ksi yield strength, this results in a factor of safety of approximately 2.6.

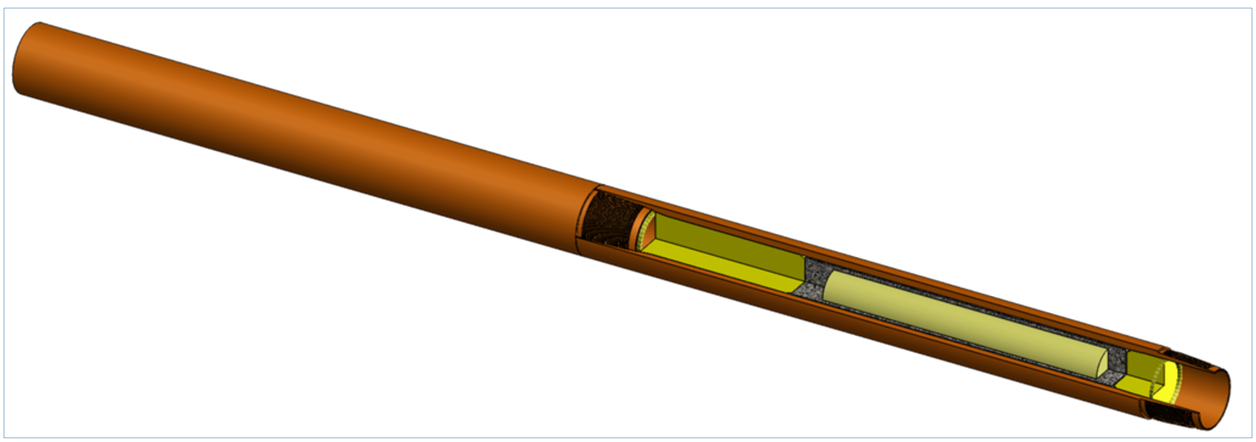


Figure 14. Option 4 (shown as 2 packages with aspect ratio shortened for illustration).

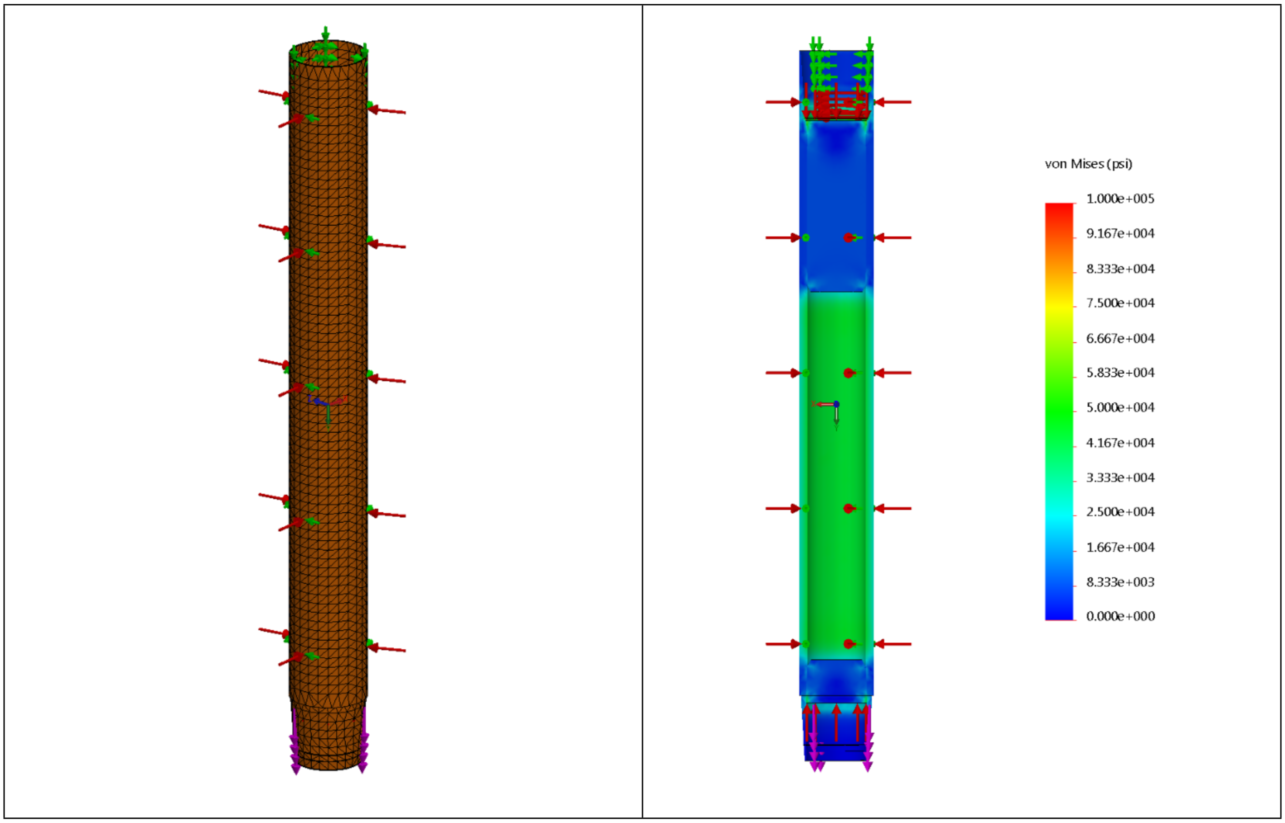


Figure 15. Design Option 4 stress analysis (aspect ratio shortened for illustration).

4.4.1 Option 4 Pros

- Based on standard size casing
- No welds in axial load path
- Dovetail threads provide good sealing against external pressure

4.4.2 Option 4 Cons

- Dovetail threads not designed repeated assembly/disassembly
- Smooth exterior requires additional external collars for handling and emplacement, which could increase the package OD beyond the 5-inch maximum diameter requirement

5. MODULAR ENHANCEMENTS FOR PACKAGES

Each of the concepts in the previous section is consistent with the envisioned handling and emplacement options (Cochran and Hardin 2015). The modular design of the packages allows for threaded connection with adjacent packages, or for the addition of threaded adapters and enhancements for lowering the waste packages into the borehole.

5.1 Fishing Adapter and Crush Box for Wireline Emplacement

A modular crumple zone could be placed on each package to absorb impact in the event of loss of control during wireline emplacement (Figure 16). A similar crumple zone adapter could be used on the lowermost package for drill-string emplacement, to limit axial load surge when the string is set on bottom.

For wireline emplacement, an adapter on the upper end of each package would include a wireline latch and fishing neck (Figures 16 and 17). The recessed latch allows the canisters to stack in the disposal zone without damaging the latch.

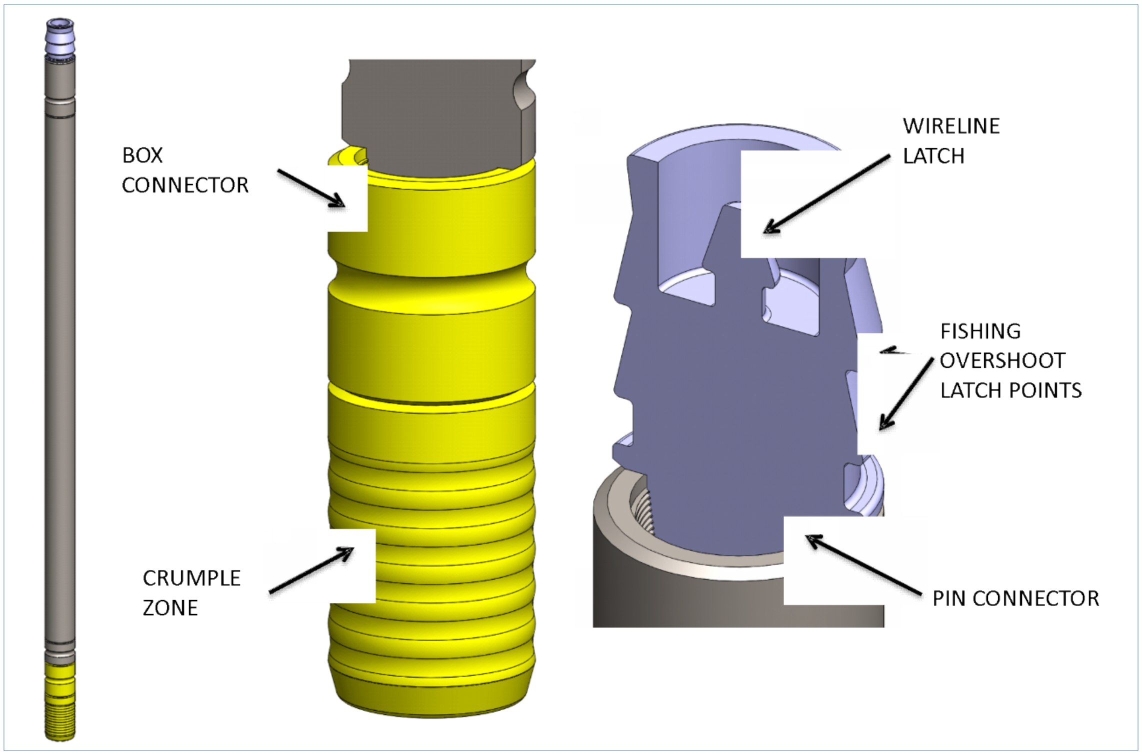


Figure 16. Modular Crush Box and Wireline Latch/Fishing Overshot.

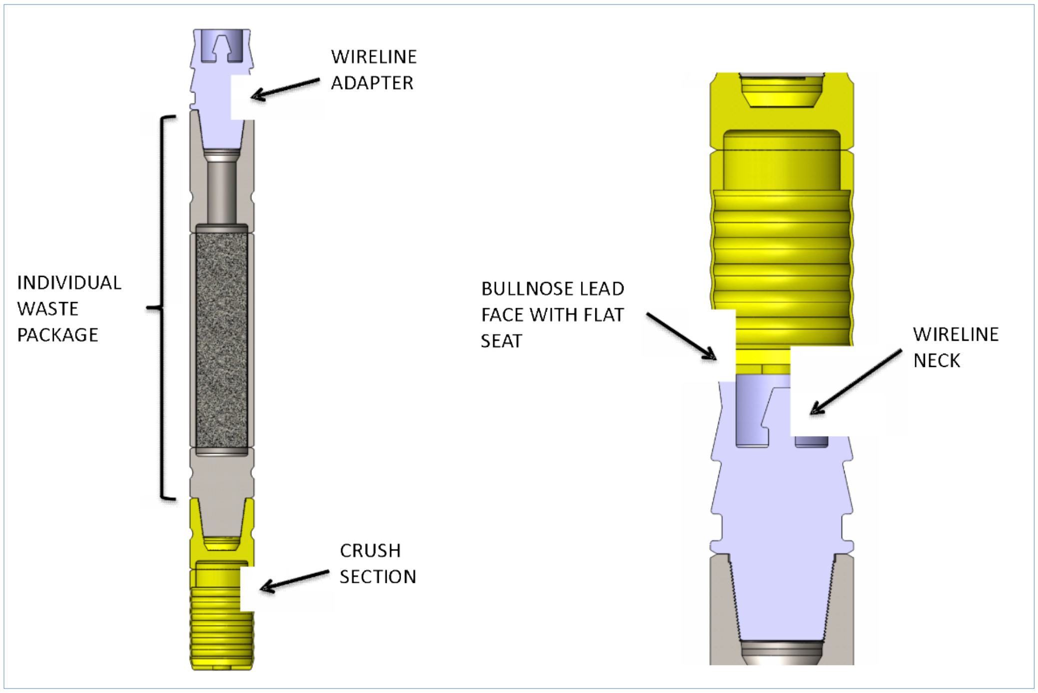


Figure 17. Package assembly for lowered individually on wireline (aspect ratio shortened for illustration).

6. REFERENCES

API Bulletin 5C3: *Bulletin on Formulas and Calculations for Casing, Tubing, Drill Pipe, and Line Pipe Properties - Sixth Edition*. American Petroleum Institute.

Arnold, B.W., P.V. Brady, S.J. Bauer, C. Herrick, S. Pye and J. Finger 2011. *Reference Design and Operations for Deep Borehole Disposal of High-Level Radioactive Waste*. SAND2011-6749. Albuquerque, NM: Sandia National Laboratories.

Arnold, B.W., P. Brady, M. Sutton, K. Travis, R. MacKinnon, F. Gibb and H. Greenberg 2014. *Deep Borehole Disposal Research: Geological Data Evaluation, Alternative Waste Forms, and Borehole Seals*. FCRD-USED-2014-000332. U.S. Department of Energy, Office of Used Nuclear Fuel Disposition. September, 2014.

Cochran, J.R. and E.L. Hardin 2015. *Handling and Emplacement Options for Deep Borehole Disposal Conceptual Design*. SAND2015-6218. Albuquerque, NM: Sandia National Laboratories.

Gourgoyne, Jr., T. Adam, K.K. Millheim, M.E. Chenevert and F.S. Young, Jr. 1986. *Applied Drilling Engineering*. Society of Petroleum Engineers.

Hardin, E.L. 2015. *Deep Borehole Field Test Requirements and Controlled Assumptions.* SAND2015-6009. Albuquerque, NM: Sandia National Laboratories.

E. Hardin (personal communication, subject: capsule mass. July 28, 2015).

DISTRIBUTION

1	MS0719	John Cochran	6234 (electronic copy)
1	MS0747	Ernest Hardin	6224 (electronic copy)
1	MS0747	Geoff Freeze	6224 (electronic copy)
1	MS1033	Jiann-Cherng Su	6916 (electronic copy)
1	MS0899	Technical Library	9536 (electronic copy)

Sandia National Laboratories